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WAVE CLOUDS ASSOCIATED WITH OBSTACLES, OBSERVED FROM ARTIFICIAL EARTH SATELLITES

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ABSTRACT. A comparatively large number of television pictures of wave clouds associated with obstacles, taken by the "Cosmòs-122" satellite, is analyzed above mountainous regions in the Urals and eastern Siberia. The characteristic scale of wave movements is determined from the television pictures. Statistical analyses of rawinsonde data on temperature and wind are used as a basis for drawing conclusions regarding the nature of the temperature stratification within the cloud layer and the wind-field pattern in the air layer below the clouds.

The graphs are provided which allow use of television pictures of wave clouds to determine the wind speed and direction.

3 figures, 12 bibliographic entries.

Television pictures of cloud covers are one of the most important forms /30* of meteorological information presently obtained from artificial earth satellites. The high resolving power of the television cameras mounted aboard the "Cosmos-122" satellite [2], has made it possible to discover a number of interesting features of the structure of cloud formations having dimensions on the order of several kilometers. In the television pictures it is possible to detect easily, in particular, wave clouds that develop on the lee side of mountain ridges. The clouds which form behind obstacles, appear in television pictures in the form of bands having a characteristic wave form that extend hundreds of kilometers downwind.

The study of conditions which are favorable for the development of clouds on the lee side of obstacles, has been the subject of a great many both

* Numbers in the margin indicate the pagination in the original foreign text.

theoretical and empirical papers [1,3,5,8,12]. The results obtained in these studies can be formulated as follows: Clouds form behind obstacles in the presence of stable stratification in the atmosphere, high rates of air flow, and significant wind shifts in the cloud layer. As a rule, the cloud bands that form in the troughs of the waves are arranged perpendicular to the direction of the air flow. The length of the lee wave changes as a function of the distribution of wind and temperature with height, and varies from 5 to 50 km.

Prior to the development of artificial earth satellites, investigators were faced with the problem of determining the length of the lee wave on the basis of a given temperature and wind speed distribution in the atmosphere. Now meteorologists have access to information on the spatial distribution of clouds behind the obstacle. The opposite problem arises in this connection, i.e., determining the direction and speed of the air flow as well as the temperature stratification of the atmosphere on the basis of television pictures of cloud cover. The meteorological literature contains scattered examples of joint analysis of television pictures of wave clouds and synoptic material [9, 10].

In contrast to previous efforts, the author has analyzed a comparatively large number of photographs of wave clouds developing behind the Urals and mountain ridges of eastern Siberia. Analysis of these pictures has shown that the wave clouds extend 100-500 km. behind the obstacles (downwind) and frequently occupy areas on the order of millions of square kilometers. /31

In working with the television pictures, the scale of the wave movements behind the obstacles was investigated first.

The statistical analysis of the data from measurements of the wave length revealed that in 50% of the cases the wave length was between 10 and 15 km., in 20% of the cases, it was between 5 and 10 km., in 20% of the cases, it was 15 to 20 km., and in 10%, it was more than 20 km. Hence, the wave length behind the obstacle was most often 10-15 km., which is in complete agreement with the theory of mountain waves [8]. It should be pointed out that wave lengths on the order of 1 km. and less could not be distinguished in the television pictures, so that no data on their reproducibility are given in the selection we have made.

The study of the atmospheric temperature stratification conditions in the presence of lee wave clouds showed that the vertical temperature gradient in the cloud layer changes within rather wide limits (from $\gamma = 0.4$ to $\gamma = 0.9$ at 100 m). Meteorological observation data from a network of ground stations indicate that mainly strato-cumulus clouds formed behind obstacles during the period in question. This may be considered an indirect proof that the temperature gradients in these regions were small as a rule.

Joint analysis of television pictures of cloud cover and wind field patterns has revealed the following features of the wind field in the layer of the atmosphere beneath the clouds: (a) the speed of the air flow increased with height, the vertical wind shear changed from $1 \cdot 10^{-3}$ to $6 \cdot 10^{-3}$ sec^{-1}, and the modal value was $3 \cdot 10^{-3}$ sec^{-1}; (b) the mean wind speed in the cloud layer (according to data from 24 measurements) was 11 m/sec, and in half the cases, it was 10 to 15 m/sec; (c) the wind direction was stable with height (the change in wind direction with height was less than 10° in 60% of the cases at 1,000 m., while it was 30° at 1,000 m. in the remaining 40% of the cases).

It follows from both the nonlinear [4, 5], and linear [8] theories of mountain waves that as the speed of the air flow increases, the wave length increases as well, all other conditions being equal. It was interesting in this regard to plot a graph showing wind speed as a function of wave length. and to use empirical data to compare the results obtained with the theoretical findings (Figure 1). Figure 1 lists the empirical data we obtained (marked by the dots), as well as the empirical curve showing the dependence of wind speed on wave length (Curve 1). For comparison, the same relationship is given (Curve 2), proceeding from linear theory,

$$L = 2\pi u \sqrt{\frac{T}{g(\gamma_a - \gamma)}},$$

where u is the mean speed of the flow, T is the absolute temperature, γ_a and γ are the adiabatic and actual vertical temperature gradients, respectively, g is the acceleration due to gravity, and L is the wave length.

The dependence of wind speed on wave length calculated by the semi-empirical formula of A. A. Dorodnitsin ($u = L^2/4$, where, L is the wave length in km., and u is the wind speed in m/sec) is represented in Figure 1 by Curve 3.

It is evident, from Figure 1, that the actual wind speed at a given wave length will be less than would be indicated by linear theory, for example. Although the number of models is small (25), the empirical relationship can obviously be used to estimate the speed of the air flow on the basis of the television pictures of cloud cover made by a satellite. /32

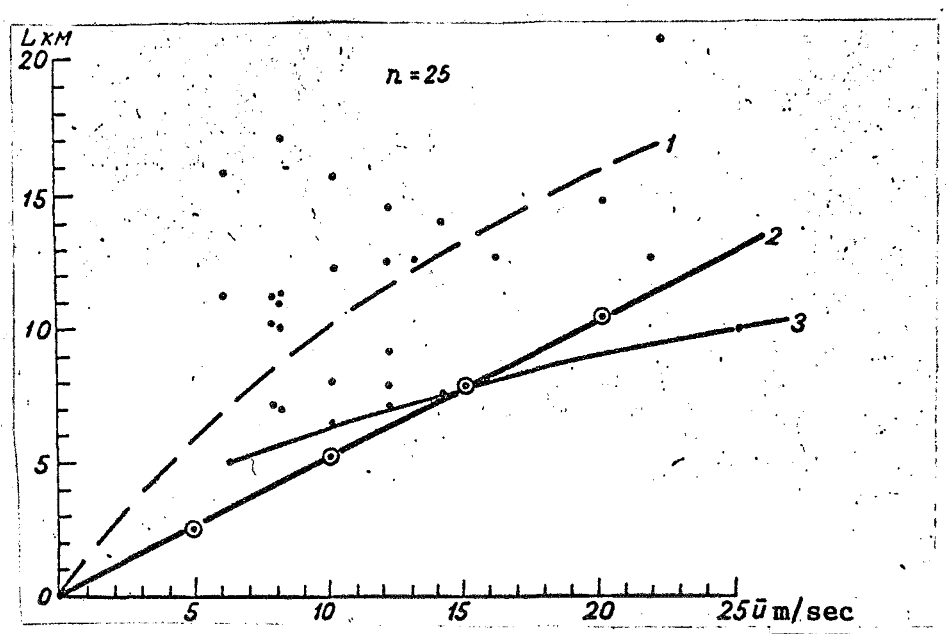

Figure 1. Wind speed versus wave length. n = number of models.

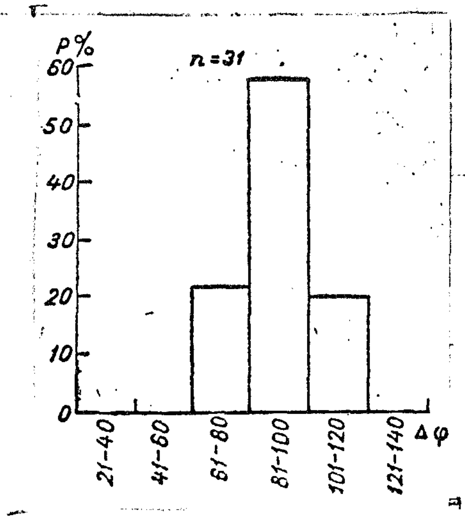

Figure 2. Mutual orientation of cloud bands and wind direction. P = probability of occurrence of various values Δφ.

Another problem of practical interest is the clarification of the mutual orientation of the air flow and the cloud bands. The empirical data on the mutual orientation of the cloud bands and the air flow are given in Figure 2. They indicate that in the majority of cases, the clouds are oriented perpendicular to the air flow. In 60% of the cases, the deviation of the orientation of the clouds from normal to the direction of the air flow (Δφ) does not exceed ± 10°, i.e., it is within the limits of accuracy of our measurements. In the remaining cases, Δφ does not exceed ± 30°.

Hence, television pictures of wave clouds that develop behind mountain ridges can be used to determine the direction of the air flow considering it to be perpendicular to the cloud bands.

Let us take an example of the identification of the direction and speed of the air flow on the basis of a television picture of cloud cover taken by "Cosmos-122" on July 21, 1966 (Figure 3). The clouds were photographed at 0912 hours, Moscow time above the Ural Mountains. Analysis of the photograph revealed that wave clouds stretched into bands were observed over a rather large area on the lee side of the mountains. The cloud bands were arranged parallel to the mountain ridge (from south-southwest to north-northeast). They were judged to be strato-cumulus clouds on the basis of the photograph and data from ground observations. Anyalysis of the aerological material indicated that at 0900 hours the atmosphere in this region was stably stratified (γ = 0.78 degrees/100 m), the wind direction did not change with height and was from the west-northwest. The wind speed increased with height and was 15 m/sec in the cloud layer.

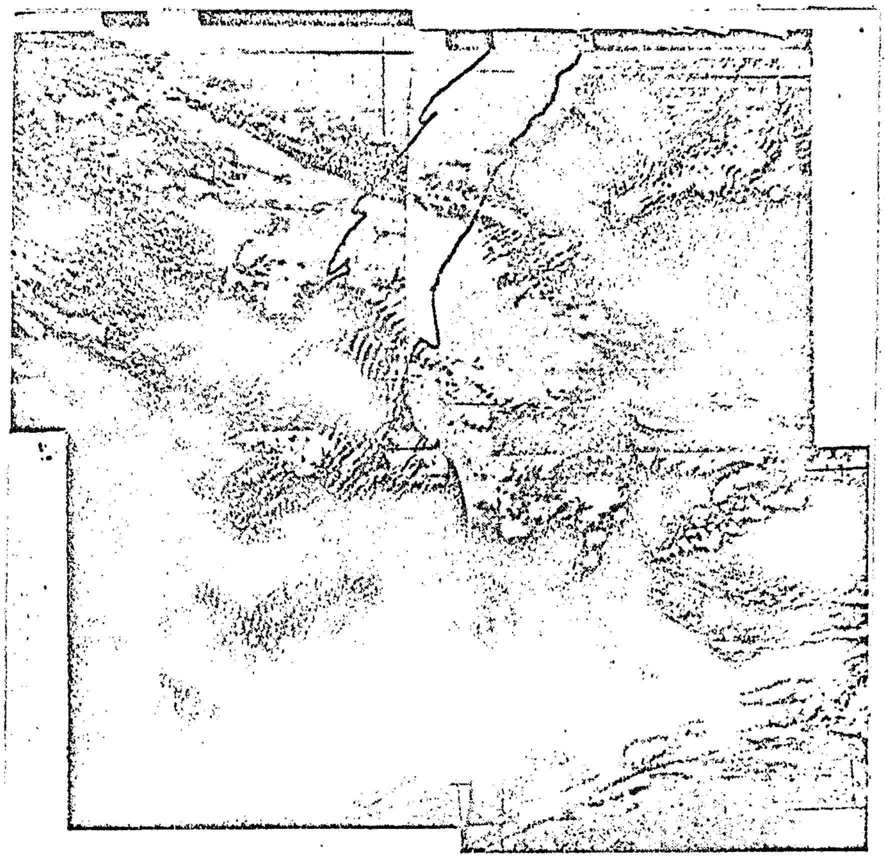

Figure 3. Television picture of cloud cover taken by "Cosmos-122" on June 21, 1966, at 0912 hours (Moscow time). The outline shows the position of the Ural Ridge. The dot shows the location of the Salekhard Station.

The wave length was determined as follows in the television picture: the distance between the n^{th} and $n + 5^{th}$ or $n + 6^{th}$ cloud bands was measured after which the average wave length was determined. In the case, which we are discussing here, the wave length was found to be 11 km. We then used the graph (Figure 1) to determine the wind speed at the cloud level. This figure was 11 m/sec. The wind speed values determined according to the theoretical straight line and along the curve, plotted using Dorodnitsin's semi-empirical formula, are 21 and 25 m/sec, respectively.

The actual wind speed in the cloud layer, as indicated by rawinsonde data collected at Salekhard, was 15 m/sec. The direction of the air flow, as identified from the picture, agreed with the true wind direction. /34

The results presented in this paper indicate that television pictures of cloud formations developing on the lee side of mountain ridges can be used to determine the direction of the air flow. Determination of the rate of air flow in the cloud layer is less reliable, but the difference between the calculated and actual data on wind speed is comparatively small. Further accumulation of data, factual data, will undoubtedly reveal closer empirical relationships and will make it possible to make a still more reliable determination of the speed of air flow on the basis of data on the spatial structure of clouds on the lee side of mountain ridges.

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